



Article Water Footprint Assessment of Major Crops in Henan Province and Reduction Suggestions

Yanbin Li¹, Yuyi Yin¹ and Wenge Zhang^{2,3,*}

- School of Water Conservancy, North China University of Water Resources and Electric Power, Zhengzhou 450046, China
- ² Yellow River Institute of Hydraulic Research, Yellow River Conservancy Commission, Zhengzhou 450003, China
- ³ Henan Key Laboratory of Ecological Environment Protection and Restoration of Yellow River Basin, Zhengzhou 450003, China
- * Correspondence: zhangwenge@yeah.net; Tel.: +86-135-2684-0719

Abstract: Henan Province, located in the North China Plain, as one of the most important grain production bases in China, is facing severe challenges of water pressure and sustainable development caused by agricultural production. In this study, water footprint (WF) estimation and sustainability assessment of crop production were carried out for wheat and maize, two major crops in the Henan Province. Based on a set of global WF benchmark values for various crops which were established by previous studies, we calculated a set of benchmark values of blue water footprint (BWF, surface water, and groundwater) for major crops in Henan Province. Four benchmark values were calculated for each crop, and we selected two of them as the optimal and sub-optimal benchmark levels. Additionally, potential blue water savings were estimated by reducing the crop-specific BWF to different benchmark levels. According to our simulations with CROPWAT 8.0, the average annual blue water footprint of wheat production in Henan Province from 2006 to 2016 was 7914 Million m³, of which about 77% is unsustainable, and that of maize production is 703 Million m³, of which about 70% is unsustainable. When reducing the water footprint of wheat production to optimal or sub-optimal benchmark levels, approximately 2742 Million m³ or 375 Million m³ blue water can be saved, and reducing that of maize production to optimal or sub-optimal benchmark levels could save approximately 214 Million m³ or 44 Million m³ blue water.

Keywords: CROPWAT 8.0; crop production; water footprint; sustainability; potential blue water savings

1. Introduction

As a populous country, China has a huge demand for grain, and Henan Province is known as "the granary of China from ancient times". In 2019, Henan Province produced nearly 67 million tons of grain, ranking second in China, wheat output (37.4 million tons) ranked first in China, and maize output (22.5 million tons) ranked fifth in China [1]. Behind this huge crop output is the huge consumption of fresh water. In 2020, the total water consumption of Henan Province was 22.292 billion m³, among which agricultural water consumption was 11.499 billion m³, accounting for 51.6% of the total water consumption. Irrigation can make up for the lack of soil moisture and improve agricultural productivity, so agriculture is the largest water user globally, and Henan Province is surely no exception [2]. In this context, studies have shown that Henan Province is facing severe water stress and widespread groundwater depletion for most of the year [3,4]. Although the use of blue water for crop production in Henan Province has become one of the major factors leading to severe water stress in the region, the province will continue to maintain or even increase its current grain production for a long time. The reason is, in consideration of national food security, the Chinese government does not allow the area of cultivated land in Henan Province to be less than 1.2 million km². Therefore, Henan Province is faced



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). with severe challenges of sustainable blue water utilization and sustainable agricultural development, and reducing the blue water use for crop production would be a major problem in this region.

The "water footprint" proposed by Hoekstra [5] has been adopted by many researchers as a non-traditional method for quantitative assessment of water resources, which can identify the time and place of water consumption. The water footprint (WF) consists of the blue water footprint (BWF), green water footprint (GWF), and gray water footprint, which correspond to the time and place of their respective water consumption. BWF refers to the consumption of blue water (surface water and groundwater resources) by a product in its supply chain or the process of production, and consumption refers to the loss of available surface water and groundwater within the catchment. Water loss occurs when water evaporates, flows back out of the river basin, joins the sea, or is incorporated into products. GWF refers to the consumption of green water (rainwater that does not become runoff) resources. Grey water footprint is a pollution-related index defined as the volume of fresh water required to absorb and assimilate a given pollutant load based on natural background concentration and existing environmental water quality standards [6].

There are various studies on the estimation of crop production water footprint (CWF) in recent years. Mekonnen and Hoekstra [7] estimated the CWFs of 126 crops world-wide and assessed the sustainability of the BWF of crop production. Siebert and Doll [8] developed a model called GCWM to compute consumptive blue and green water use and virtual water content of crops, they computed the corresponding yields of 26 crops under irrigation (blue and green water consumed) and rain-fed conditions (only green water consumed). Pfister and Bayer [9] studied the CWF from the perspective of temporal resolution, and calculated the CWF by multiplying the water stress index they developed for 11,000 watersheds worldwide by the monthly crop irrigation water consumption. Sun et al. [10] evaluated the green and blue virtual water that generated from transporting these crops among areas. Sun et al. [11] estimated the WF of main crops in the Hetao irrigation district of China based on a calculation method modified by themselves.

The number of studies on the water footprint of specific crop production has been increasing in recent years, but beyond quantitative assessment of the CWF, quite few studies have looked at providing information for formulating the regional crop-specific BWF reduction targets. Setting reasonable reduction targets for the BWFs of specific crops will help water conservation work be carried out more purposefully, and ultimately help relieve the pressure on local freshwater resources and achieve sustainable use of water resources.

Herein we estimated the BWF and GWF of wheat/maize production of the 18 cities in Henan Province, and the CROPWAT 8.0 model was used in this process. There are two options in this model, we chose the "irrigation schedule option" instead of the "crop water requirement (CWR) option" because the former is more accurate than the latter, and it was recommended by the *Water Footprint Evaluation Manual* [12]. Based on that, this study assessed the sustainability of the BWF of wheat/maize production in Henan Province. Furthermore, we calculated a set of benchmark values of crop production BWFs based on previous research results [13]. A benchmark value of the BWF is a target to which we could aim to reduce the current BWF of crop production. We selected two benchmark values of BWF from the four we calculated as the optimal and sub-optimal benchmark levels for the 18 cities in the province. The sub-optimal benchmark level as an initial reduction target is easier to achieve for the cities with difficulty in achieving the optimal benchmark level. This paper calculated the potential blue water savings corresponding to the different reduction targets. The period of this study is from 2006 to 2016.

2. Materials and Methods

2.1. Study Area

Henan Province is located in the middle of China $(31^{\circ}23'-36^{\circ}22' \text{ N}, 110^{\circ}21'-116^{\circ}39' \text{ E})$, and in the south of the North China Plain, which is known for agriculture from ancient China. The climate here is a continental monsoon climate that transitions from the northern subtropical zone to the warm temperate zone. Most of Henan Province is located in the warm temperate zone while the southern part of it is located in the subtropical zone. Henan Province covers an area of 167,000 km² and has 18 cities. Figure 1 shows the names and locations of the 18 cities in Henan Province and the location of Henan Province in China.



Figure 1. The 18 cities in Henan Province and the location of Henan Province in China.

2.2. Water Footprint Estimation

Since accurate data required for gray water footprint calculation is difficult to obtain, only blue and green water footprints are estimated. In this paper, the water footprint refers to the sum of the blue water footprint and green water footprint. This paper estimated the WF per ton of wheat/maize production (m^3/t) in 18 cities from 2006 to 2016, and the total water footprint of wheat/maize production in million m³ per year (Mm³/yyear) in the whole province from 2006 to 2016.

2.2.1. CROPWAT 8.0 Model

To estimate the green and blue WF of crop production, green and blue water evapotranspiration during crop growth needed to be estimated first. We achieved that with a model called CROPWAT 8.0, which was developed by the FAO [14].

There are two alternative options provided in the model: the "CWR option" (assumed optimum condition) or the "irrigation schedule option" (included the possibility of specifying actual irrigation supplies in a timely manner) [12]. The total ET and the resultant total WF calculated by these two options are similar, but the blue-green WF ratio is quite different. Given the irrigation schedule option has higher accuracy than the CWR option [12], we chose the irrigation schedule option for estimations. Refer to the Water Footprint Evaluation Manual [12] for more specific operation methods. The water footprint is the sum of the blue, green and grey water footprints. As it is difficult to obtain data to estimate gray water footprint, only blue water footprint and green water footprint are estimated in this paper.

$$WF = BWF + GWF$$

where the WF, BWF and GWF are in m^3/t .

$$BWF = \frac{CWU_{blue}}{Y}$$
$$GWF = \frac{CWU_{green}}{Y}$$

where CWU_{blue} is the blue component in crop water use (m³/ha), CWU_{green} is the green component in crop water use (m³/ha), and Y is the crop yield Y (ton/ha).

$$CWU_{blue} = ET_{blue} \times 10$$

 $CWU_{green} = ET_{green} \times 10$

where the factor 10 converts water depth in millimeters into water volume per land surface (m^3/ha) , and ET_{green} and ET_{blue} are green and blue water evapotranspiration (mm), respectively.

$$ET_{blue} = min(net irrigation, actual irrigation requirement)$$

where net irrigation (mm) and actual irrigation (mm) are calculated by CROPWAT 8.0.

$$ET_{green} = ET_a - ET_{blue}$$

where ET_a (mm) is the adjusted crop evapotranspiration calculated by the irrigation schedule option.

$$ET_a = K_s \times ET_c$$

where K_s is the stress coefficient and ET_c is the crop evapotranspiration (mm).

$$ET_c = K_c \times ET_0$$

where K_c is the crop coefficient and ET_0 is the reference crop evapotranspiration which was estimated by CROPWAT 8.0 in mm.

$$WF_{prov} = \sum (WF^i \times P_i)$$

where WF_{prov} (Million m³/year) is the sum of water footprint of 18 cities per year, WF^i is the WF (m³/t) of the *i*th city per year, and P_i is the crop yield of the *i*th city per year.

2.3. Sustainability of Blue Water Footprint

Mekonnen and Hoekstra [7] estimated the f_{uns} around the world. Basing on that, we estimated the sustainability of the BWF consumed in the major crops production in the Henan Province.

$$BWF_{uns} = BWF \times f_{uns}$$

where BWF_{uns} is the unsustainable blue water footprint (m³/year), BWF is the blue water footprint (m³/year), and f_{uns} is the fraction of the unsustainable blue water footprint.

$$f_{uns} = \frac{max[(BWF_{tot}(y) - BWA(y)), 0]}{BWF_{tot}(y)}$$

where $BWF_{tot}(y)$ is the total blue water footprint for year y, and BWA(y) is the total available blue water for year y.

2.4. Blue Water Footprint Reduction

2.4.1. Blue Water Footprint Benchmark Level (BWF Benchmark Level)

Mekonnen and Hoekstra [13] ranked the CWF of the major crops worldwide, providing the CWF of the major crops in the 10th (CWF 10th), 20th (CWF 20th), 25th (CWF 25th), and 50th (CWF 50th) percentiles, respectively. Those results provided a benchmark for CWFs across the globe. This paper assumes that the ratio of BWF to GWF in the CWF of the specific crop in this paper is the same as that of BWF to GWF in the CWF benchmark value of the specific crop provided by Mekonnen and Hoekstra [13].

$$BWF_{benchmark} = WF_{benchmark} \times \frac{BWF}{GWF}$$

where $BWF_{benchmark}$ is the benchmark level of wheat or maize production blue water footprint (m³/t), the $WF_{benchmark}$ is the CWF 10th, CWF 20th, CWF 25th, and CWF 50th, respectively, provided by Mekonnen and Hoekstra [13] (m³/t), and the BWF and GWF are, respectively, the blue and green WF of wheat or maize production in Henan Province estimated earlier in this paper (m³/t). The BWF benchmark level calculated with CWF 10th, CWF 20th, CWF 25th, and CWF 50th are hereinafter referred to as the first, second, third, and fourth BWF benchmarks, respectively.

In this paper, four different BWF benchmarks of wheat/maize production for each city in Henan Province are calculated, corresponding to the CWF at the four different production percentiles mentioned above. We compared the blue water savings generated by each city when four different BWF benchmark level values were targeted for the BWF decrement. We selected two benchmark values for wheat and maize production BWF in Henan Province after taking various factors into consideration, which were called the optimal and the sub-optimal benchmark levels of BWF.

2.4.2. Blue Water Footprint Reduction

The BWF that could be reduced was estimated by reducing the current BWF to the benchmark level of BWF.

where $BWF_{reduction}$ is the part of the blue water footprint of crop production that could theoretically be reduced (m³/t), that is, saved.

$$BW_{save} = BWF_{reduction} \times P$$

where BW_{save} is the potential consumptive blue water savings yearly (m³/year), P is the crop production yearly (ton/year).

3. Results

3.1. The WF of Wheat/Maize Production

We estimated the blue-green water footprint of wheat and maize production in 18 cities from 2006 to 2016, and summed up the data for the whole province over the years as shown in Table 1. The blue water footprint of wheat production in Henan Province was the highest (11,356 million m³) in 2013, and the lowest (3667 million m³) in 2015. From 2006 to 2016, the average annual blue water footprint consumption was 7914 million m³, accounting for 28% of the total water footprint. The blue water footprint of maize production is far lower than that of wheat. The blue water footprint of maize production in the whole province in 2014 was the highest (2525 million m³), and the lowest was 0 in the year 2007. The blue water footprint of maize in most other years was below 500 million m³, with an average of

703 million m³. The average ratio of the blue production water footprint of maize to the total water footprint is 6%.

		N	heat		Maize				
Year	Blue WF	Green WF	WF	Proportion of BWF in WF	Blue WF	Green WF	WF	Proportion of BWF	
_	(N	/lillion m ³ /year)	(%)	(1	(%)			
2006	7984	19,962	27,946	29%	80	9634	9714	1%	
2007	8199	20,453	28,651	29%	0	10,067	10,067	2%	
2008	7239	21,721	28,960	25%	76	10,430	10,505	3%	
2009	5438	20,965	26,403	21%	413	10,568	10,981	4%	
2010	12,093	15,791	27,884	43%	201	10,829	11,029	4%	
2011	9839	16,709	26,548	37%	228	10,803	11,030	5%	
2012	7237	19,872	27,109	27%	201	12,466	12,667	4%	
2013	11,356	17 <i>,</i> 592	28,948	39%	2419	12,549	14,968	18%	
2014	4884	20,618	25,502	19%	2525	9866	12,392	20%	
2015	3667	24,569	28,236	13%	1248	13,065	14,312	9%	
2016	9116	20,145	29,260	31%	344	14,077	14,421	2%	
Average	7914	19,854	27,768	28%	703	11,305	12,008	7%	

Table 1. Water footprint of wheat and maize production during 2006–2016 in Henan Province.

We averaged the WF (m^3/t) of wheat/maize production for each city in Henan Province from 2006 to 2016, and showed their spatial distribution in Figure 2. The BWF (m^3/t) of wheat was higher in western and northern Henan, but lower in southern Henan. The highest was found in San Menxia (583 m^3/t), followed by Zhengzhou (544 m^3/t) and Luoyang ($524 \text{ m}^3/t$), and the lowest was found in Zhoukou ($33 \text{ m}^3/t$), Zhu Madian $(34 \text{ m}^3/\text{t})$, and Xinyang $(94 \text{ m}^3/\text{t})$. The WF (m^3/t) of wheat was higher in central Henan, western Henan, and southern Henan, but lower in eastern Henan. The highest values were found in San Menxia (1400 m³/t), Luoyang (1349 m³/t), and Zhengzhou (1280 m³/t), while the lowest values were found in Zhoukou (586 m^3/t) and Shangqiu (724 m^3/t).

The blue WF of maize was higher In western and central Henan, but lower in eastern and southern Henan. The BWF of maize in Zhengzhou (109 m^3/t), San Menxia (174 m^3/t), Ping Dingshan ($105 \text{ m}^3/t$), Shangqiu, and Zhu Madian was 0. In the central, western, and southern Henan, the WF of maize production was higher and in northern Henan it was lower. Zhengzhou (1034 m³/t), Sanmenxia (966 m³/t), Ping Dingshan (893 m³/t), Shangqiu (559 m^3/t), and Jiaozuo (552 m^3/t) were the lowest in the province.

3.2. Sustainability of Blue Water Footprints of Wheat and Maize Production

Mekonnen and Hoekstra [7] calculated the fraction of unsustainable global blue water footprint according to the environmental flow standard and available renewable water resources. We assessed the sustainability of local wheat and maize production through the annual fraction of the unsustainable blue water footprint of Henan obtained from them. According to our estimation, the blue water footprint of major crops production in Henan is unsustainable.

3.2.1. Wheat

According to calculation, the wheat production in the province consumes an average of 7914 million m³ (Mm³) of blue water every year, of which about 77% is unsustainable. In Figure 3, we show the spatial distribution of unsustainable blue water consumed by wheat production in Henan Province, and the proportion of green water, sustainable blue water, and unsustainable blue water in the water footprint per ton of wheat production in each city.



Figure 2. The spatial distribution of the blue, green, and total WF (m^3/t) of wheat and maize production in Henan Province.



Figure 3. The distribution of unsustainable blue WF (Mm^3 /year) of wheat and the composition of WF (m^3 /t) in each city.

From the perspective of water footprint components per ton of wheat production, the proportion of blue water (sustainable and unsustainable) footprint per ton of wheat production in the five northern cities and the eastern and western cities was about 40%, but there is a big difference between the proportion of sustainable and unsustainable

blue water among these cities. The proportion of unsustainable blue water in five cities in northern Henan was the highest: Xinxiang (38%), Anyan (37%), Hebi (37%), Jiaozuo (36%), and Puyang (31%). The proportion of sustainable blue WF was only about 5%. The proportion of unsustainable blue WF in central, western, and eastern Henan was about 20–30%, and the proportion of sustainable blue water was about 15%, except in Xuchang (5%), Shangqiu (5%), and Nanyang (4%). In addition, the proportion of unsustainable blue WF in the three cities in the southeast was relatively low: Zhoukou (4%), Zhu Madian (4%), and Xinyang (6%). The proportion of sustainable blue water was about 2%, and the total proportion of blue water footprints does not exceed 10%. Since the three cities are located in a humid zone, this may have something to do with the climate. However, Nanyang is also in the humid zone, with the proportion of unsustainable blue water being 21%, and the proportion of sustainable blue water being 4%. It can be seen that the climate humidity is not completely positively related to the proportion of blue water consumed by crop production.

From the perspective of the annual total unsustainable blue WF, Xinxiang (715.3 Mm³/year), Shangqiu (838.5 Mm³/year), and Nanyang (741.5 Mm³/year) have the highest consumption, accounting for 38% of the total. The consumption of central and northern cities closely followed, at about 270 Mm³/year–600 Mm³/year, while that of western and southeast cities was less than 230 Mm³/year. In the cities with a high total unsustainable blue WF, the unsustainable blue WF per ton of wheat production was more than 20%, and the wheat planting area and yield were also high. Taking Xinxiang as an example, the average wheat planting area from 2006 to 2016 was 332,000 hectares, and the average annual yield was 2,230,312 tons.

3.2.2. Maize

The maize production in 18 cities consumed 703 million m³ of blue water. Although this is only about 9% that of wheat production, about 70% of it was unsustainable. As we did in Figure 3, Figure 4 shows the spatial distribution of unsustainable blue water consumed by maize production, and the proportion of green WF, sustainable blue WF, and unsustainable blue WF in the water footprint per ton of maize production in each city.



Figure 4. The distribution of unsustainable blue WF (Mm^3 /year) of maize and the composition of WF (m^3 /t) in each city.

Although maize production has a smaller dependence on blue water compared to wheat, the proportion of blue water (m^3/t) of maize production of the total WF (m^3/t) of

maize production in 18 cities was mostly around 10%. Additionally, there were 12 cities where the unsustainable blue WF (Mm³/year) of the total blue WF (Mm³/year) were above 50%.

In terms of consumption of unsustainable blue WF (Mm³/year), Anyang (52.6 Mm³/year), Zhengzhou (51 Mm³/year), Ping Dingshan (50.7 Mm³/year), Luoyang (50.3 Mm³/year), Xuchang (43 Mm³/year), and Nanyang (40.3 Mm³/year) were the six top cities. The results showed that the maize production in Shangqiu and Zhu Madian completely consumed green water, so the consumption of blue water was 0.

Zhengzhou's maize production averages 732,719 tons per year, less than 60% of Xinxiang, its neighbor to the north. However, the proportion of unsustainable blue WF (m^3/t) in Zhengzhou (70 m³/t) was nearly three times that of Xinxiang (20 m³/t), resulting in the average annual unsustainable blue WF (Mm³/year) consumed by Zhengzhou's maize production (51 Mm³/year) being two times that of Xinxiang (25 Mm³/year). Regions with a very high proportion of unsustainable blue water per unit yield, even under the condition of low yield, will consume more unsustainable blue water than regions with a low proportion and high crop yield. The total amount of unsustainable blue WF consumed by maize production in the whole province was 493 Mm³/year, and that of wheat was 6065.4 Mm³/year, which was above 10 times that of maize.

3.3. Blue Water Footprint Reduction

The Optimal/Sub-Optimal BWF Benchmark Level

In this paper, four different levels of BWF benchmarks were calculated for wheat and maize production in Henan Province. The results are shown in Table 2. These benchmark values provide a comparative basis for the blue water footprint of wheat and maize production consumption in each city. If the wheat production of all cities in the province were to reduce their BWF using the first or second BWF benchmarks as the target, the crop production in Henan Province would achieve a blue water savings of 2742 million m³/year or 375 million m³/year, accounting for about 36% and 5% of the province's average annual BWF of wheat production, respectively. In the province, only one of the 18 cities currently has a wheat BWF below the first BWF benchmark, 11 cities have it below the second benchmark, and 13 cities have it below the third benchmark.

	Blue Water Footprint Benchmark Levels (m ³ /t)								
City Name	Wheat				Maize				
	First	Second	Third	Fourth	First	Second	Third	Fourth	
Zhengzhou	251	422	454	591	65	70	73	97	
Kaifeng	227	382	411	535	52	56	58	78	
Luoyang	230	386	415	540	58	62	65	87	
Ping Dingshan	179	300	323	420	59	64	66	89	
Anyang	255	428	461	600	38	41	43	57	
Hebi	259	434	467	608	34	37	39	52	
Xinxiang	267	449	483	629	17	19	19	26	
Jiaozuo	251	420	453	589	18	20	20	27	
Puyang	251	421	454	590	19	20	21	28	
Xuchang	208	349	376	489	44	48	50	67	
Luohe	243	408	439	571	52	57	59	79	
San Menxia	247	414	445	579	90	97	101	136	
Nanyang	149	250	269	350	20	22	22	30	
Shangqiu	208	349	376	489	0	0	0	0	
Xinyang	49	82	89	115	17	18	19	25	
Zhoukou	33	55	60	78	22	24	24	33	
Zhu Madian	26	43	46	60	0	0	0	0	
Jiyuan	226	379	408	531	19	21	21	29	

Table 2. The BWF benchmark levels in 18 cities of Henan Province.

For maize production, if the BWF of maize production in each city was reduced to the first or fourth BWF benchmark levels, there would be a corresponding blue water savings of 214 million m³/year or 44 million m³/year, representing about 6% and 1.2% of the BWF of maize production, respectively. Compared with their four benchmark values, only two cities in the province have values lower than the first and second benchmarks of maize production BWFs, and four and eleven cities have values lower than the third and fourth benchmarks of maize BWFs, respectively.

We selected two benchmark values for wheat and maize production BWFs in Henan Province as the optimal and the sub-optimal benchmark levels of the BWF. We choose the first of the four calculated benchmark values, the lowest, as the optimal benchmark level for both wheat and maize production because this level will lead to the greatest blue water savings, and in theory, it can be achieved [13]. Then we compared the blue water savings generated by each city when reducing their current BWF down to four different BWF benchmark values. We found that about half of the cities in the province were unable to meet the second benchmark value of BWF for wheat production and the fourth benchmark value of BWF for maize production. Therefore, we selected them as the sub-optimal benchmark for wheat and maize production BWFs. We believe that it would be more practical for these cities to use the sub-optimal benchmark level as an initial BWF reduction target.

Taking the optimal and the sub-optimal BWF benchmark levels of wheat production as the reduction target of the current BWF, the corresponding blue water savings in 18 cities had different performances, as shown in Figure 5.



Figure 5. Potential blue water savings of wheat production at optimal or sub-optimal benchmark level in 18 cities.

It can be seen that the current wheat production BWF in Zhoukou has been lower than the optimal benchmark value, so the potential blue water savings under the standard of this study is 0. Nanyang has the highest potential blue water savings under the optimal benchmark value (345 Mm³), while the blue water savings under the sub-optimal benchmark value is 0. This is because although the BWF per unit yield of wheat in Nanyang is no higher than the sub-optimal benchmark value, its wheat yield is very high. Therefore, the reduction of wheat BWF targeted at the optimal benchmark in Nanyang can bring much higher blue water savings than those cities with very low yield and BWF per unit yield above the sub-optimal benchmark. In Xinyang, Sanmenxia, Pingdingshan, Luoyang, Kaifeng, and Zhengzhou, 375 Mm³ of blue water can be saved if the current BWF is reduced to the sub-optimal benchmark, while 1161 Mm³ of blue water can be saved achieving the optimal benchmark. However, these are the six cities with the highest BWF per unit yield of wheat in the province. It would be more practical to set the sub-optimal benchmark as a BWF reduction target, since it is likely to be very difficult to use the optimal benchmark as an initial reduction target.

For maize production, Figure 6 shows the potential blue water savings of maize production in 18 cities with the reduction to the optimal and sub-optimal WF benchmark levels correspondingly.



Figure 6. Potential blue water savings of maize production at optimal or sub-optimal benchmark levels in 18 cities.

With a reduction to the optimal benchmark level, the potential blue water savings of maize production in Shangqiu and Zhu Madian were 0. Potential blue water savings of maize production in the other 16 cities was about 214 Million m³ in total, accounting for about 30% of the blue WF of maize production. When reducing the WF of maize production to the sub-optimal benchmark level, there are 11 cities with a potential blue water savings of 0, while about 44 Million m³ of potential blue water savings could be attained in the other 7 cities, representing about 6% of the blue water footprint of maize production.

4. Discussion

This study first estimated the BWF and GWF of the major crops wheat and maize in Henan Province, then evaluated the sustainability of the BWF of major crops' production, and finally calculated the potential BWF reduction and blue water savings. Part of this work was accomplished by combining the data extracted from two previous studies of Mekonnen and Hoekstra [7,13]. Comparing to Cao [15], the BWF of wheat and maize production in Henan Province we estimated is slightly lower and the GWF is slightly higher. Both studies simulated evaporation using the CROPWAT 8.0 model, but we chose the irrigation schedule option in the model while Cao chose the CWR crop water requirement option in the model. The differences in these two options can partly explain the differences in results. In the assessment of unsustainable BWFs and potential BWF reductions, the results are subject to a number of limitations and uncertainties inherent to the data used in the current study. For example, one of the two studies by Mekonnen and Hoekstra [7] did not consider the effect of artificial reservoirs on runoff, while the other [13] did not take climate and soil factors into consideration.

The figures we reported regarding water use in this paper should be considered as an indicator that shows the efficiency and sustainability of water use in crop production in Henan Province instead of absolute values.

This study only focuses on the sustainability of blue water, but as a resource that consumes a higher proportion of crop production per unit of output, green water should also be considered [16,17]. In addition, the impact of water quality on the sustainability and effectiveness of blue water, as a factor that has been neglected all along, should be taken into consideration in future studies [7].

The estimates of unsustainable blue water and BWF reduction are rough. In estimating the BWF reductions, we assume that the blue-green ratio in the current CWF is the same as in the WF benchmark. This means that the blue-green ratio remains the same when reducing the CWF to the WF benchmark level. If the reduction of CWF is achieved by reducing evaporation, this assumption will be questioned. However, it has been pointed out that CWF reduction is mainly achieved by increasing yield and less by reducing evapotranspiration around the world [6,18–20], which supports the hypothesis that when the WF is reduced to the baseline level, the blue-green ratio will remain unchanged [6,7].

Some views hold that it is not necessary to determine different regional benchmark values according to the crop growth conditions or regional economic development degree of each region. First of all, as far as crop growth conditions are concerned, climate and soil are non-negligible factors when considering evapotranspiration and yield of farmland; however, the major factor in the BWF and GWF (m^3/t) is agricultural management, not the crop growing environment [6,21]. Through proper nutrition, water, and soil management, most crops in different climatic regions of the world can significantly increase their yields without increasing, or even reducing, field evapotranspiration [22]. Secondly, in terms of regional economic development, it has been proven that the water productivity associated with the best 10% of global crop yield can be found in both low-income and high-income countries [13]. However, as proposed by [23,24], it would be beneficial to develop a WF benchmark based on the achievable goals of the best available technologies and practices. After synthesizing the two perspectives, instead of taking the WF of the 10th percentile of global crop production as a default benchmark level like other researchers do, we provide two criteria, the optimal benchmark level and the sub-optimal benchmark level, with the latter one selected from a provincial perspective based on the number of cities with estimated blue water savings of 0.

Henan Province is a major agricultural and grain-producing province in China. Food production in this place plays an important role in the country and has made important contributions to national food security. However, long-term and large-scale grain production has caused serious pressure on its water resources. The research results show that blue water consumption caused by main crop production in Henan Province is highly unsustainable. With 1.41 billion people in China, Henan Province, as "the granary of China", meets

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the food needs of 18% of the world's population. Sustainable food production and water use in this region should be considered significant issues on a global scale. Additionally, because of the limited water resources in the global cycle and their importance for survival and development, the water problem in a region should not be regarded as a problem only in that region or within the region's country, but should be given due consideration to the responsibility of the regional water problem in terms of global water security.

This study will be helpful for the government and enterprises to formulate appropriate strategies to assess the sustainability of water for crop production and estimate potential blue water conservation in Henan Province. Previous studies on reducing water pressure have shown that water productivity of irrigation and rain-fed crops needs to be improved by increasing yields and reducing unwanted evaporation [18,20]. Secondly, it can be coordinated with other policy instruments such as distributing water from low-value crops to high-value crops, controlling the expansion of irrigation area [25,26], and setting WF caps for each watershed [25,27]. Finally, Henan Province, as one of the top three agricultural provinces in grain dispatch, can take the value of virtual water into consideration and make additional compensation in food price setting.

5. Conclusions

As an important grain base, the sustainability of agricultural development and water resource utilization in Henan Province has not been paid enough attention. The major findings of this study are as follows: (i) The WF of wheat production is higher in the central, the western, and the northern parts of Henan. The WF of maize production is higher in the central and the western parts of Henan. (ii) The proportion of unsustainable BWF consumption in wheat production in most areas of Henan Province is about 30%, except the southeastern part of Henan Province. (iii) Reducing the BWF of current wheat production in Henan Province to the optimal and sub-optimal benchmark levels, respectively, could bring blue water savings of 2741 Mm³/year and 375 Mm³/year. Reducing the BWF of current maize production in Henan Province to the optimal and sub-optimal and sub-optimal benchmark levels, respectively, could bring blue water savings of 214 Mm³/year and 44 Mm³/year.

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Data Availability Statement: Publicly available datasets were analyzed in this study. The climate data can be found here: CMDC (cma.cn) (accessed on 10 January 2017). The parameters of crops can be found here: Crop evapotranspiration. Guidelines for computing crop water requirements (fao.org) (accessed on 12 June 2022). The sowing and harvesting date of crops can be found here: Henan Meteorological Bureau (cma.gov.cn) (accessed on 2 August 2022). The yearly f_{uns} of Henan was obtained from professor Mesfin M. Mekonnen and are available from him with his permission (obtained on 29 July 2022). The WF benchmarks are openly available in Web of Science at https://doi.org/10.1016/j.ecolind.2014.06.013, reference number [13] (accessed on 6 July 2022).

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